Meter-Scale Friction Experiments with Gouge: Heterogeneities and Friction Properties

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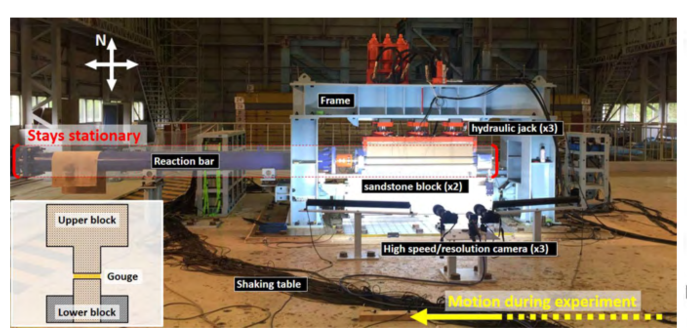
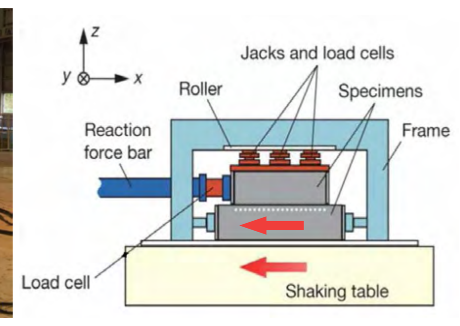
Introduction

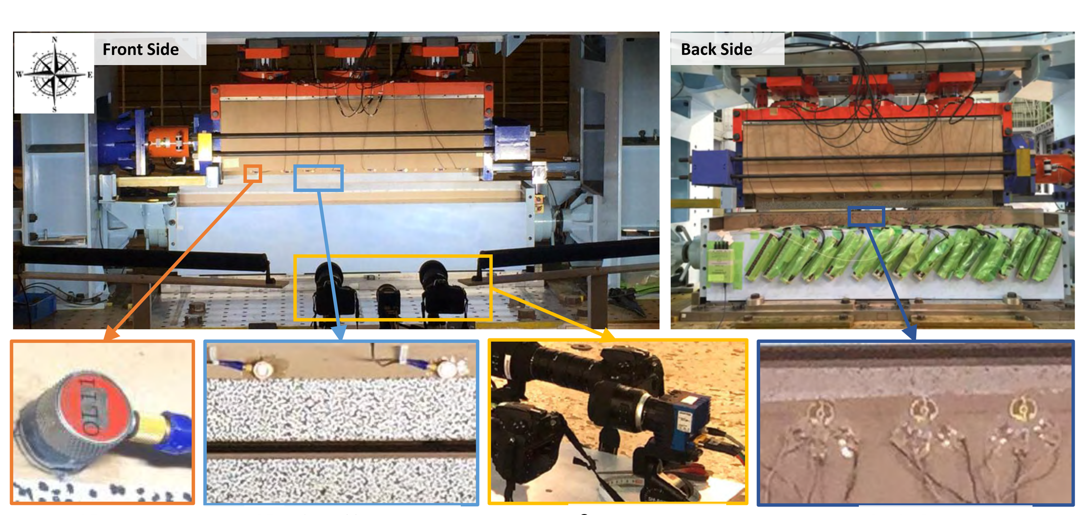
The Groningen gas field is one of the largest onshore gas fields in the world. Induced seismic events due to gas production have been recorded in this field since the 1990s, the largest of which is the2012 ML3.6 Huizinge earthquake. In order to simulate rupture and sliding of induced seismic events or natural earthquakes, it is necessary to use a constitutive law for fault friction. However, existing friction laws are based on experiments at centimeter scale, while an earthquake rupture in nature occurs over hundreds of meters of fault area or more. **This raises the question of whether the friction law derived from the small-scale experiments can be directly applied to such a large fault area, or whether larger scale heterogeneities affect the frictional strength and the constitutive parameters.** To answer this, fault friction must be tested at least at the mesh scale of finite element models, i.e. at the scale of at least 0.5 to 2 meters. In 2018, we conducted a series of experiments using the large-scale friction apparatus driven by a shaking table at NIED, Tsukuba, Japan to explore the possibility of scale-dependent frictional properties of simulated fault gouges. We completed 34 experiments with 3 different gouge length(0.5 m, 1 m, 1.5 m), using simulated gougs prepared from Slochteren sandstone core materials.

Methods





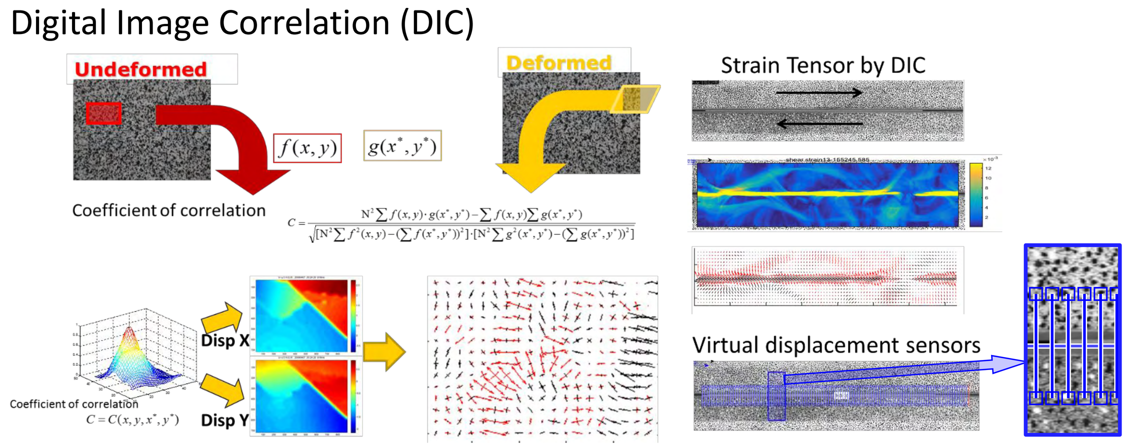
We performed the world's first meter scale friction experiments on simulated gouge filled fault, making use of the Large-Scale earthquake simulator(the shaking table) at NIED (the Japanese National Institute for Earth Science and Disaster Resilience). The shaking table in NIED allows direct shear experiment of large (up to 1.5m) blocks of rock at variable velocities.



Before experiment		
One pressure sheet scan		
During experiment		
Strain Gages	120 channels	1Mhz
AE	16 channels	1Mhz
LDT	6 channels	1kHz
Slow camera	36M Pixels	0.5Hz
Fast camera	2M Pixels	500 ~ 1000Hz
After experiment		
~6 fault gouge samples for thin section		
one photo scan of gouge layer topography		

As shown in the table, a variety of data logging systems has been used to record the experiments continuously at high frequency. The images of the front surface were captured by an industrial camera at 500 or 1000 Hz and another two high resolution cameras at 0.5Hz.

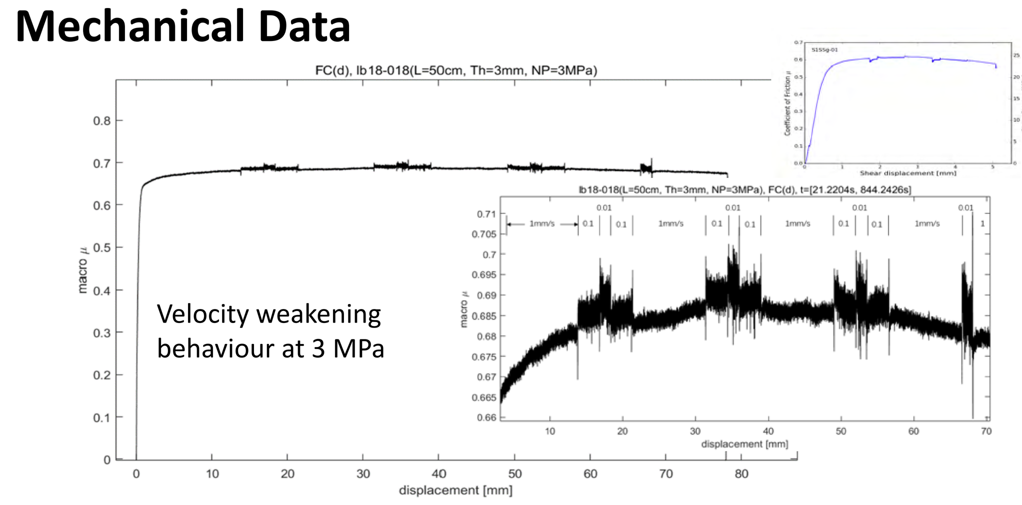
Digital Image Correlation (DIC)



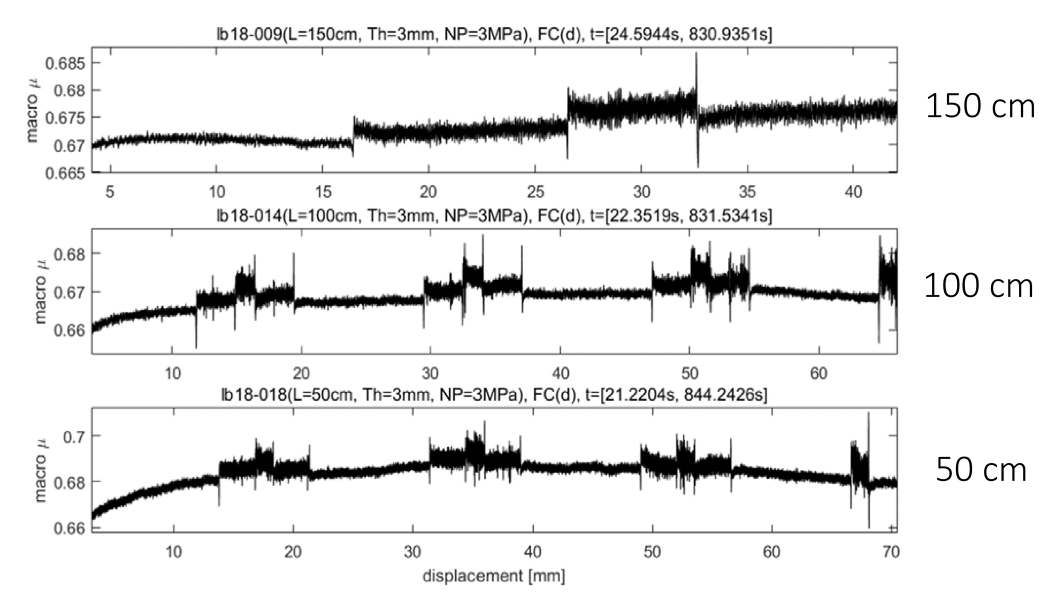
Digital image correlation(DIC) is an optical method that employs image registration techniques for accurate full-field displacement and strain measurement. With the displacement obtained, we can also deploy virtual cross-fault displacement sensors along the fault to get the temporal-spatial distribution of fault displacements.

Results

Mechanical Data

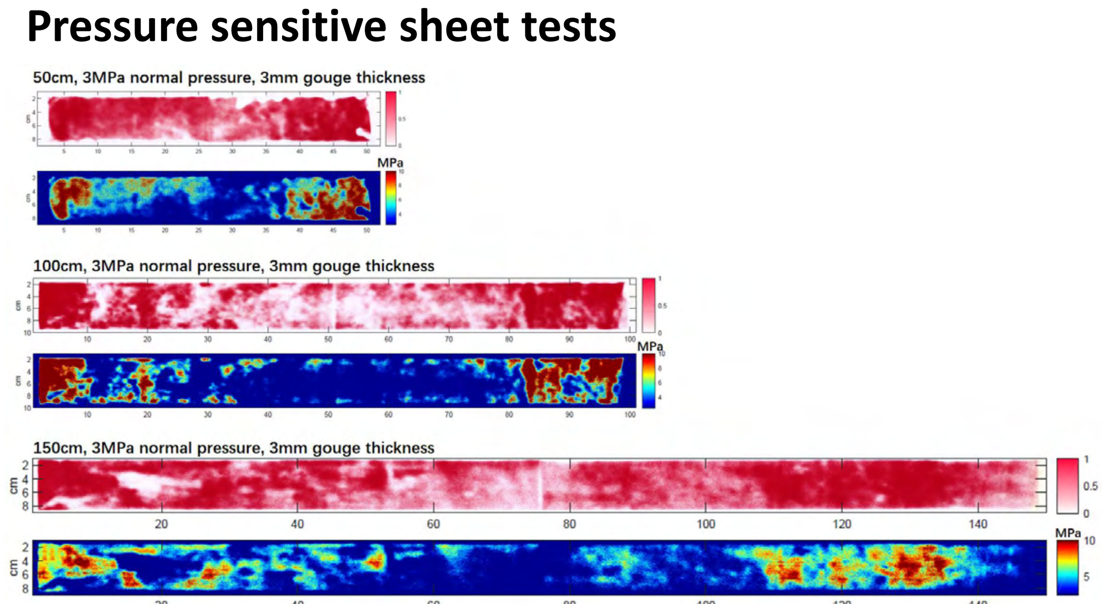


Typical mechanical data (μ vs displacement) obtained for 0.5m gouge length, 3mm gouge thickness and 3MPa normal stress, velocities ranging from 0.01 to 1mm/s. μ is constant for full displacement but decreases systematically with increasing V (velocity-weakening behavior).



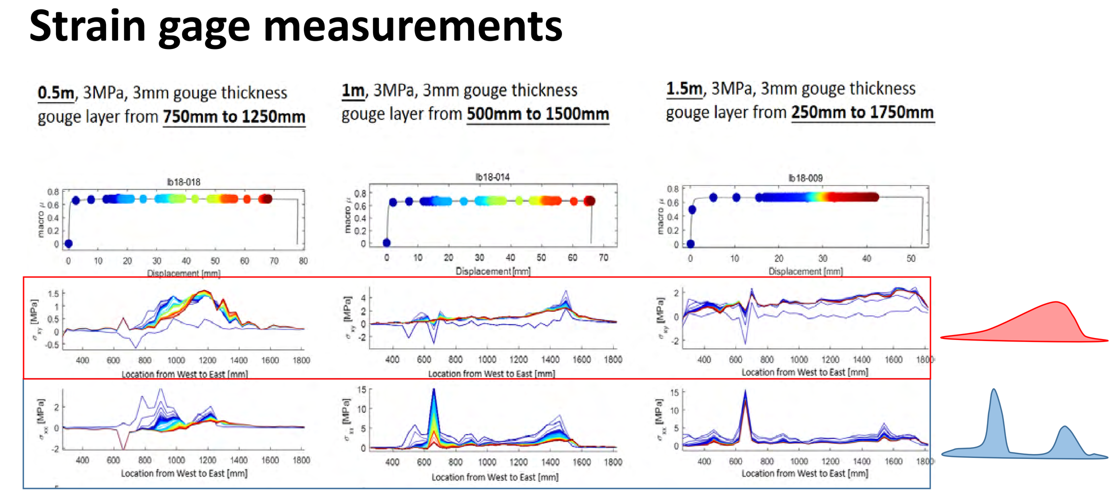
Similar behavior can be seen from the 1.5m and 1m gouge length experiments.

Pressure sensitive sheet tests



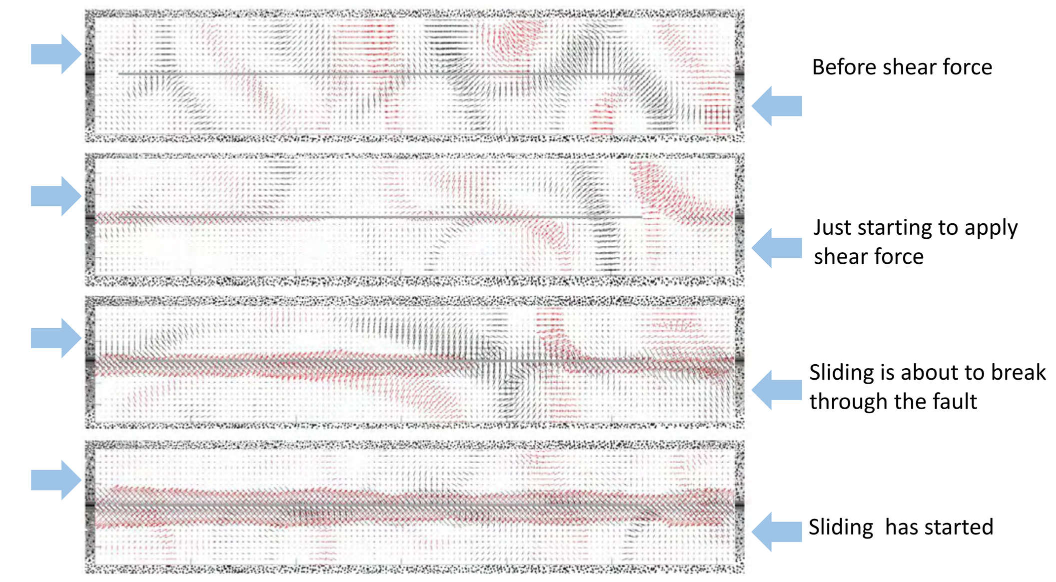
From the pressure sensitive sheet tests give the normal stress distribution after the application of normal stress to the prepared gouge layer. The distribution of normal stress before experiment(or the initial contact area) is distributed non-uniformly across the fault, concentrating on the edges. It means there is already some distribution of mechanical asperities when shearing starts.

Strain gage measurements



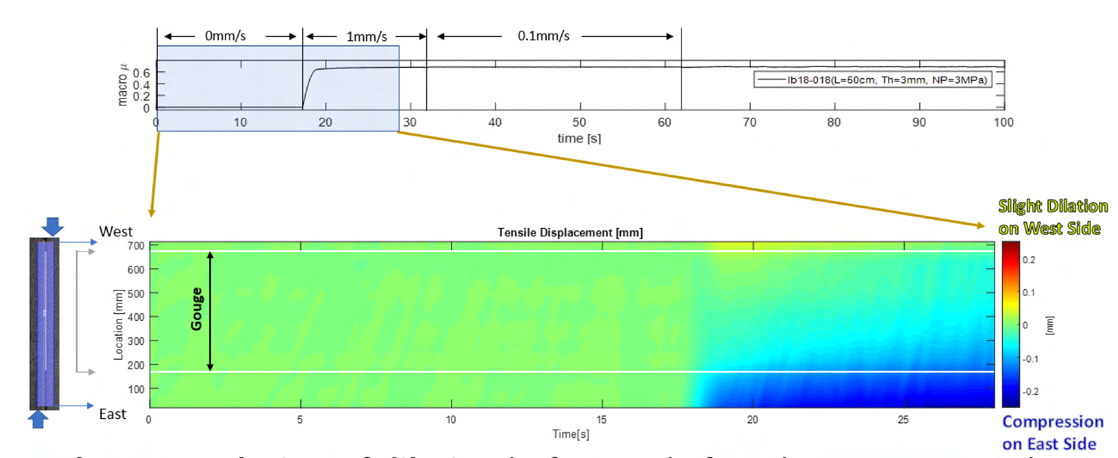
Strain gauge data from experiments with 3 mm gouge thickness at 3 MPa normal stress and variable length. The first figure in each column is the macroscopic friction coefficient and color dots correspond to different color curves in the subsequent figures, which are shear stress and normal stress. The stress distribution of all experiments start out differently and evolves with time and displacement. At the beginning of all experiments (blue curves), shear stress is distributed more symmetrically, and the normal stress is concentrated on both ends, which is consistent with the pressure sheet results. After shearing starts (yellow and red curves), the shear stress tends to concentrate to the right while normal stress tends to be more uniformly distributed.

Strain tensor evolution by DIC

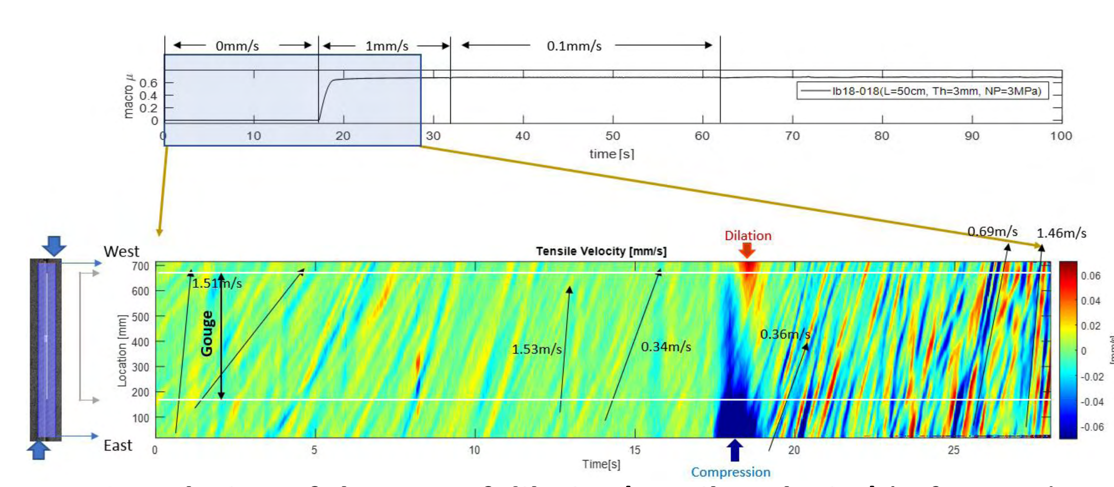


Strain tensor distributions over the sandstone blocks obtained using DIC. The gray bar indicates the location of the gouge layer. The strain field is continuously evolving. Before shear load is applied, there is already localization of deformation due to the variation in normal stress. These localization features are not necessarily along the fault, which means that under only normal load, the gouge is not participating much in the deformation. After shear load is applied, localization of deformation occurs along the gouge-filled fault.

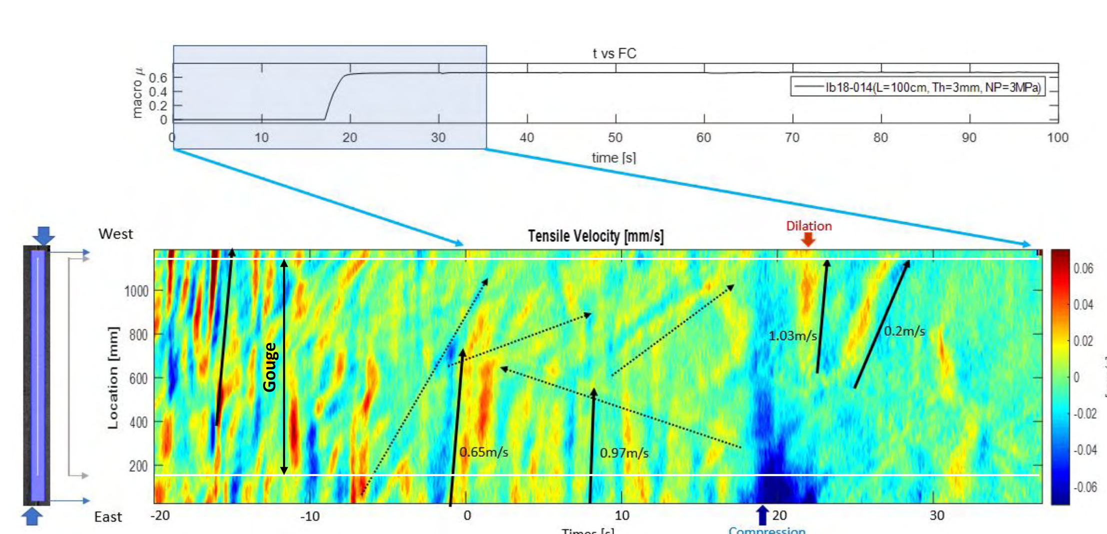
Temporal and spatial (T-S) evolution of fault displacement



The T-S evolution of dilation before and after shear. Positive values correspond to dilation and negative values to compaction. The blue area in the small image on the left shows the locations of the virtual displacement sensors in the sample, and the gray bar corresponds to the location of the fault gouge(half a meter in length). Data is from the experiment with 0.5 m gouge length, 3MPa normal stress, and a gouge thickness of 3 mm. The vertical displacement is very small before shear load is applied (< 0.02 mm). After shear load is applied, there is significant compaction on the east side(~0.2mm) and some dilation(~0.05mm) on the west side. On the east side of the fault, a sudden increase in compaction can be seen, which is the result of the lack of support of the gouge on the outer side of the fault.

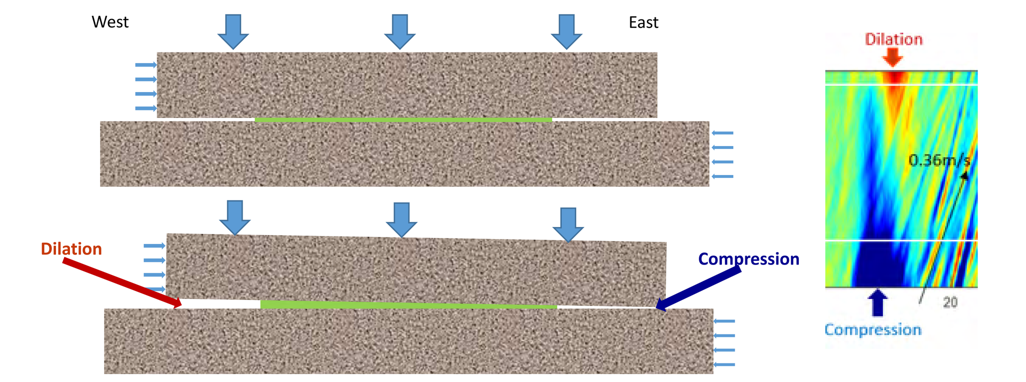


T-S evolution of the rate of dilation(tensile velocity) before and after shear. There are waves of dilation propagating through the fault. Although the displacement modulation during shear is not qualitatively different from what happened beforehand, except that is magnitude is much bigger.



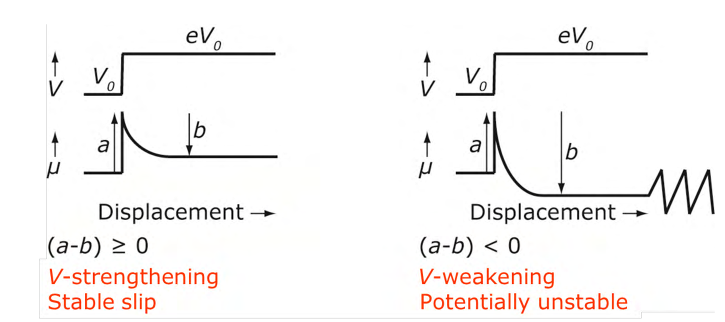
The T-S map of dilation rate of the 1m length experiment. There are also waves of dilation going through the sample.

Upper block tilting

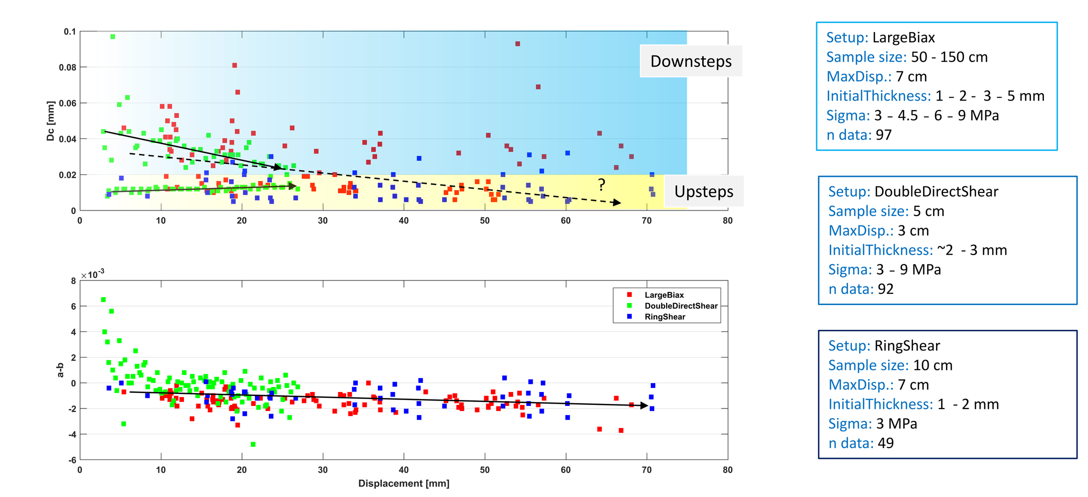


When shear load is applied, more compression occurred on the east side of the fault, while the west side of the fault experienced more tensile displacement. The overall effect is that the upper block is tilting to the east side (or rotating clockwise).

Rate and state friction law

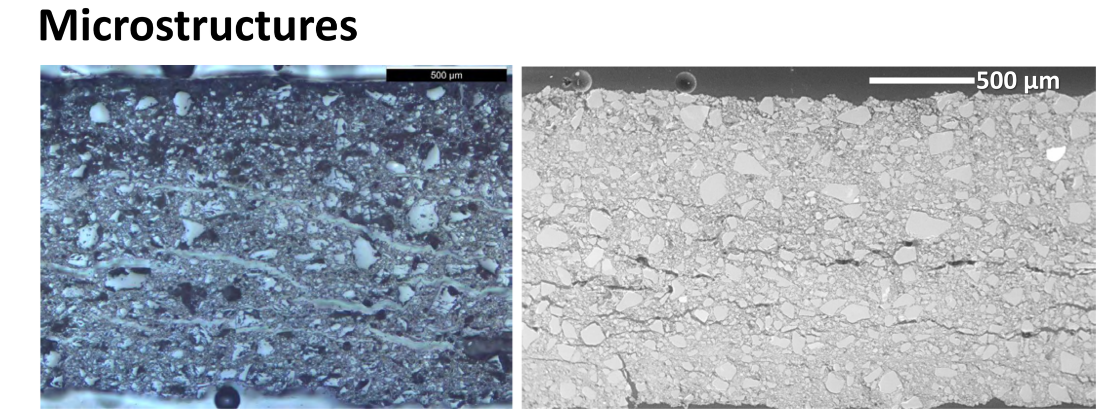


The Dieterich rate-and-state friction(RSF) law is used for understanding the velocity dependence and fault stability.



d_c and *(a-b)* versus displacement. The data points from different experiment fall into the same envelope. If there is any effect of fault scale, it is less pronounced than the slip history.

Microstructures



The microstructure of one of the large scale friction experiments at NIED. Both right lateral Riedel shear band and horizontal shear band can be seen. The length scale and aggregation of these shear bands are very similar to those typically observed in cm-scale samples. It seems that the fine scale at which the friction properties are controlled is smaller than the cm-scale and that heterogeneities at other scales average out. Presumably, this is because the overall friction behavior and the overall relation between shear stress and normal is linear.

Conclusions

1) For a fault filled with Slochteren sandstone gouge, the rate and state friction properties of large samples are not different from cm scale samples…

2).. even though heterogeneity was observed in many aspects such as contact conditions, slip and strain distribution

3) Size does not seem to affect Rate-and-State friction behavior at length scales ranging from cm to 1-2m, for gouge thickness of a few mm.

Acknowledgements

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